Processing and Characteristics Evaluation of Magnesium Alloy Hybrid Nanocomposite Featured With Nano Zirconia Particles: Ultrasonic-Aided Stir Cast Process

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Abstract: This study was done to analyse the addition of carbon nanotubes and zirconia nanoparticles to AZ31 magnesium alloy made by ultrasonic aided stir casting affects its mechanical and wear properties. Nanocomposite variants with 3 wt% CNT and ZrO₂ (1–5 wt%) were produced and evaluated for tensile, compressive and tribological performance. The results showed that the strength and wear resistance were better, with the best results seen at 3 wt% ZrO₂. The hybrid method combines structural reinforcement with surface protection from ceramics and makes these composites good candidates for use in lightweight and long lasting vehicle brake discs..

# Introduction

Magnesium alloys are increasingly favored in automotive sectors due to their low density and good mechanical properties. However, their poor wear resistance and relatively low strength limit critical structural uses. Carbon nanotubes (CNTs) offer high tensile strength and electrical conductivity, while nano-zirconia (ZrO₂) particles provide thermal stability and surface hardness [1]. Combining these reinforcements through a hybrid strategy offers a path toward enhanced functional performance. Hybrid carbon-based nanofillers have become increasingly popular for improving magnesium composites [2-5]. According to adding carbon nanotubes and reduced graphene oxide (rGO) to magnesium matrix composites greatly increased their mechanical strength, resistance to corrosion and biocompatibility. AZ31/TiC composites were made to study [6-8] using ultrasonic vibration assisted friction stir processing that produced finer grains and higher microhardness and examined the dry sliding wear of AZ31 ZrO₂ nanocomposites and found that the ceramic reinforcement increased the load bearing capacity resulted in lower wear rates [9-11].

An overview of AZ31–CNT composites made by powder metallurgy was given [12-14] emphasized the difficulties with interfacial bonding and dispersion. For the AlO₃ addition in AZ91E, combined mechanical and ultrasonic dispersion that improved strength and produced a more even distribution of reinforcement. Bimodal composite coatings of AlO₃–ZrO₂–CNTs were investigated [15-16], and observed improved fretting wear resistance and microstructural integrity. It was utilized FSP with CeO₂ and ZrO₂ reinforcements resulted in noticeable increases in corrosion, wear and mechanical resistance [17-20].

According to [21] AZ91D–Al₂O₃ composites made with ultrasonic assisted stir casting have better sliding wear behavior because of increased matrix hardening and particle distribution. Mg–ZrO₂ nanocomposites [22] and they using FSP and showed improved corrosion resistance and refined grains. It has improved the compatibility and performance of zirconia coated MWCNTs in composite matrices [23-25]. The AZ31–B₄C composites was mad using ultrasonic stir casting and found improvements in the tribological characteristics of dry sliding. In their assessment of FSP for AZ31 surface composites [26], It has emphasized the method impact on localized strengthening, defect reduction, and grain refinement [27-30]. It suggested surface modification of graphene oxide with D-glucose that greatly enhanced anticorrosive performance and offered promise for protective magnesium coatings [31-33]. A thorough analysis of hybrid magnesium composites was provided [34] and emphasized the importance of reinforcement techniques and the trade offs between wear resistance and mechanical strength and in their discussion of laser cladding with chip regenerated powder [35] and focused on enhancements in material utilization and surface characteristics that are pertinent to the surface hardness of magnesium.

This study investigates the effects of CNT and nano-ZrO₂ integration into AZ31 via ultrasonic-assisted stir casting. The focus lies in examining how increasing ZrO₂ concentrations influence mechanical and wear properties.

# Materials and Methods

## Materials

The matrix material was chosen to be AZ31 magnesium alloy because it has a good strength to weight ratio. The alloy was melted in a crucible furnace at 650 °C and then warmed carbon nanotubes and zirconia nanoparticles were added to the melt. We stirred the reinforcements mechanically at 600 rpm to make sure they were better wet and spread out. After that we used a 20 kHz probe to agitate them with ultrasonic waves for 2–4 minutes [36-39]. This ultrasonic treatment worked well to break up nanoparticle clusters and spread them out evenly throughout the matrix. The slurry was poured into steel moulds that had already been heated and left to harden at room temperature.

## Composite Formulations

**TABLE 1.** Composite Configurations Table

|  |  |
| --- | --- |
| **Sample ID** | **Composition** |
| Sample 1 | AZ31 (Unreinforced) |
| Sample 2 | AZ31 + 3 wt% CNT |
| Sample 3 | AZ31 + 3 wt% CNT + 1 wt% ZrO₂ |
| Sample 4 | AZ31 + 3 wt% CNT + 3 wt% ZrO₂ |
| Sample 5 | AZ31 + 3 wt% CNT + 5 wt% ZrO₂ |

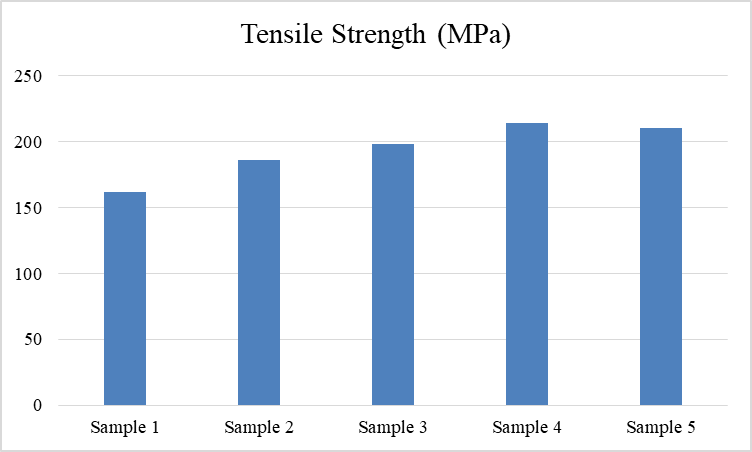
# Results and Discussion

## Tensile Strength

Adding carbon nanotubes and zirconia nanoparticles to AZ31 composites always made their tensile strength better. The hybrid reinforcement technique worked well to improve load transmission and microstructural stability. Sample 4 (3 wt% CNT + 3 wt% ZrO₂) had the highest tensile strength, which was 214 MPa. This was the best ratio of reinforcement. Sample 5 starts to go down after this point which shows that nanoparticles are clumping together and the efficacy of interfacial bonding is going down. The hybrid CNT-ZrO₂ system did far better than the unreinforced matrix (162 MPa) and the CNT only composite (186 MPa) which proves that the two types of reinforcement work together [40-45].

**TABLE 2**Tensile Strength

|  |  |
| --- | --- |
| **Sample** | **Tensile Strength (MPa)** |
| Sample 1 | 162 |
| Sample 2 | 186 |
| Sample 3 | 198 |
| Sample 4 | 214 |
| Sample 5 | 210 |



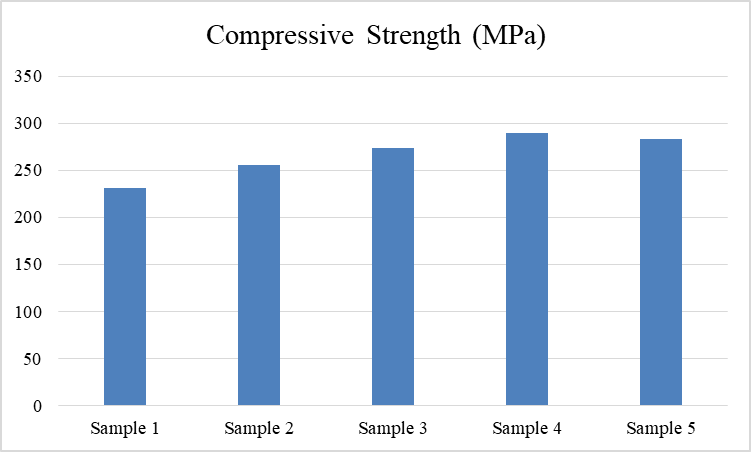
**Figure 1.** Tensile Strength

## Compressive Strength

As ZrO₂ nanoparticles act as crack arresters and stress redistributors during loading their addition to CNT reinforced AZ31 greatly increased compressive strength. The maximum compressive strength of 290 MPa was demonstrated by Sample 4 contained 3 weight % CNT and 3 weight % ZrO₂. This was a significant increase above the unreinforced alloy of 231 MPa. This improvement was done by enhanced particle matrix bonding and matrix integrity. A minor decrease in Sample 5 indicates that too much reinforcement can cause agglomeration would lessen the toughening impact a little [46-52].

**TABLE 3.** Compressive Strength

|  |  |
| --- | --- |
| **Sample** | **Compressive Strength (MPa)** |
| Sample 1 | 231 |
| Sample 2 | 256 |
| Sample 3 | 274 |
| Sample 4 | 290 |
| Sample 5 | 283 |



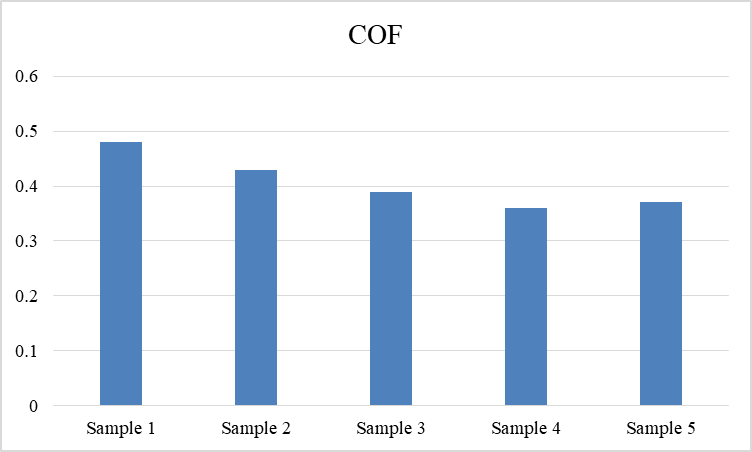
**Figure 2.** Compressive Strength

## Wear Resistance

ZrO₂ nanoparticles improved wear resistance in CNT reinforced AZ31 composites by increasing the surface hardness and reducing material loss during sliding and the best interfacial bonding and reinforcement dispersion were demonstrated by Sample 4 which contained 3 weight % ZrO₂ and had the lowest coefficient of friction of 0.36 and wear rate of 1.74 × 10⁻⁴ mm³/N·m. The strong ceramic particles were able to withstand abrasive forces and act as solid lubricants to regulate frictional behaviour and the higher wear rate in Sample 5 suggests that increased ZrO₂ loading may be the starting point for particle aggregation [53].

**TABLE 4.** Wear Resistance

|  |  |  |
| --- | --- | --- |
| **Sample** | **Wear Rate (mm³/N·m)** | **COF** |
| Sample 1 | 3.42 × 10⁻⁴ | 0.48 |
| Sample 2 | 2.61 × 10⁻⁴ | 0.43 |
| Sample 3 | 2.19 × 10⁻⁴ | 0.39 |
| Sample 4 | 1.74 × 10⁻⁴ | 0.36 |
| Sample 5 | 1.85 × 10⁻⁴ | 0.37 |



**Figure 3.**Wear Resistance

# Applications in Brake Discs

Materials with remarkable wear resistance, thermal stability and mechanical strength are needed for automotive brake discs and these requirements are met by the created AZ31, CNT and ZrO₂ hybrid nanocomposites provides excellent tribological qualities, increased surface hardness and increased tensile and compressive strength. Reduced rotor wear, improved resistance to heat degradation and steady braking performance under dynamic loads are all direct results of these enhancements. The composite containing 3 weight % ZrO₂ showed the best performance to microstructural integrity balance makes it a perfect fit for lightweight braking components of the future [54-55].

# Conclusion

This study shows that ultrasonic assisted stir casting is a good way to make composites out of magnesium alloy AZ31 that are strengthened with nano ZrO₂ and multi walled carbon nanotubes. The hybrid reinforcement method made wear resistance, compressive resilience and mechanical strength all much better. In every way that was measured, Sample 4 have 3 weight % ZrO₂, did the best. These results show that AZ31/CNT/ZrO₂ composites could be good materials for car brake disc systems as they are lightweight and have good performance. They are also important because they don't wear out quickly, can handle heat and last a long time.

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